Alternatives Analysis Workshop on Life Cycle Impacts & Exposure Assessment

Dr. Sangwon Suh & Dr. Arturo Keller

Bren School of Environmental Science and Management
University of California, Santa Barbara

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OVERVIEW OF LIFE CYCLE CONCEPTS AND TOOLS

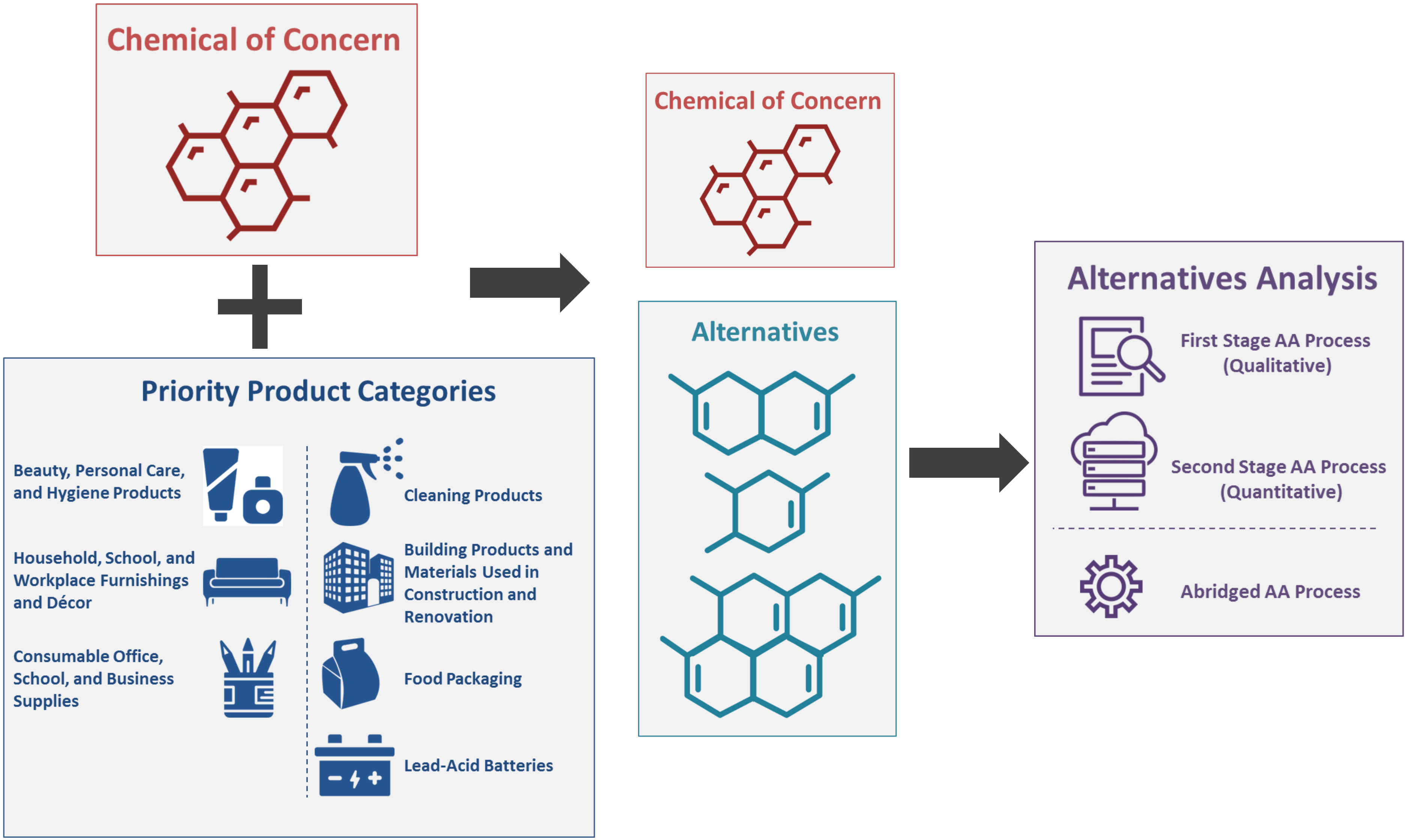
Dr. Sangwon Suh (Aug9th, 10:20am-12:00pm)

Outline

- Overview of AA
- Relevance of LCA to AA
- Recap of webinar (Life cycle thinking)
- How can LCA help AA
  - First Stage
  - Second Stage

Overview of AA

AA Simple Diagram



Alternatives Selection

Chemicals

1 Candidate Chemical List

A compilation of potentially harmful chemicals.

Based on 23 auhoritative lists.

List changes triggered by:

- Authoritative list changes
- Stakeholder petitions
- DTSC Rulemaking

Candidate Chemical database:
www.calsafer.ca.gov

Product
(Product-ChemicalCombinations)

2 Priority Products

Selection criteria:

1. Potential for exposure to the Candidate Chemicals
2. Potential for harm to human health or the environment

Products selected from categories in the Priority Product Work Plan.

Products are adopted through a transparent rulemaking process with stakeholder input.

Stakeholders may submit petitions recommending potential Priority Products.

Alternatives Analysis
(Industry Step)

3 Alternatives Selection

Manufacturers must ask:

Is the chemical necessary?

Is there a safer alternative?

Have regrettable substitutes been avoided?

Manufacturers weigh trade-offs, taking into account ecological, life cycle, and economic impacts to produce an Alternatives Analysis (AA) report.

- Manufacturer recommends selected alternative
- Confidential business information is protected
- Transparent evaluation of AA with public input

4 Regulatory Response

Possible Regulatory Responses:

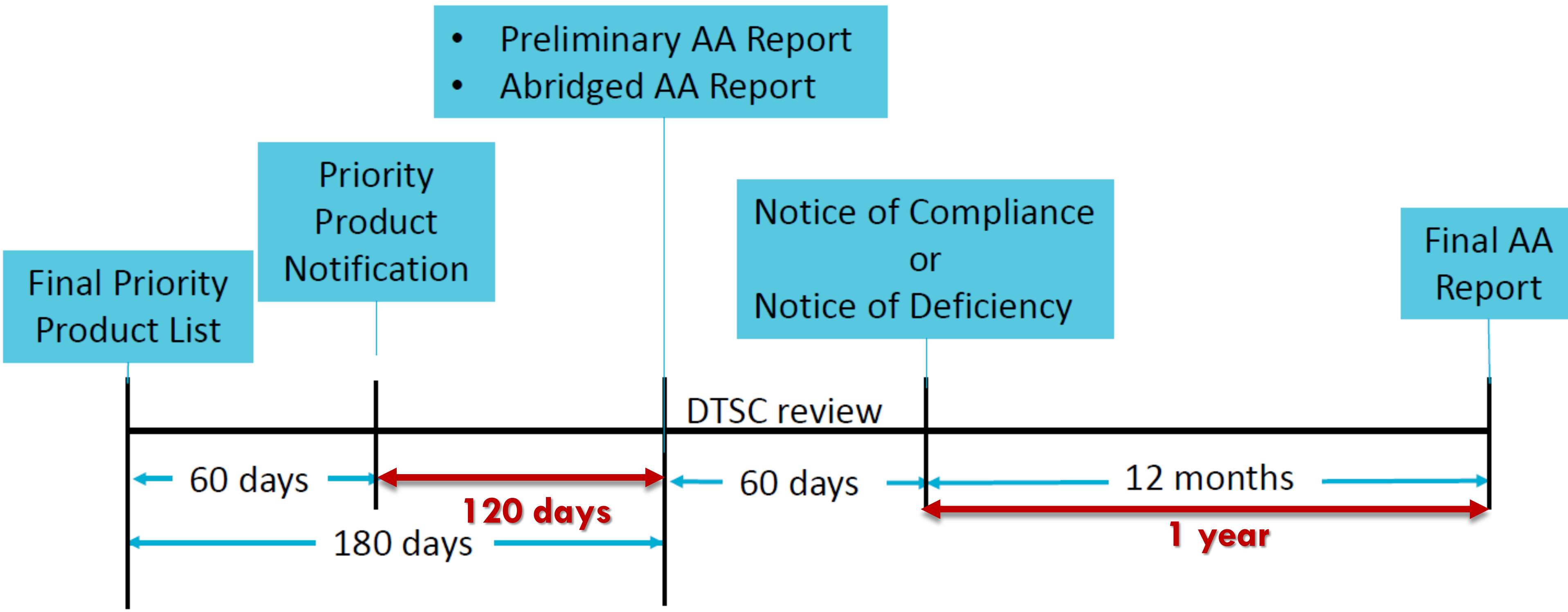
- Additional information to DTSC
- Additional information for consumers
- Additional safety measures
- Restrictions or prohibitions on sales
- End-of-life product steward-ship
- Research funding

Regulatory Responses are implemented where additional protection to public health and the environment is warranted.

Figure I-1 Major Elements of SCP Regulations

From AA Guide p2

AA Timeline



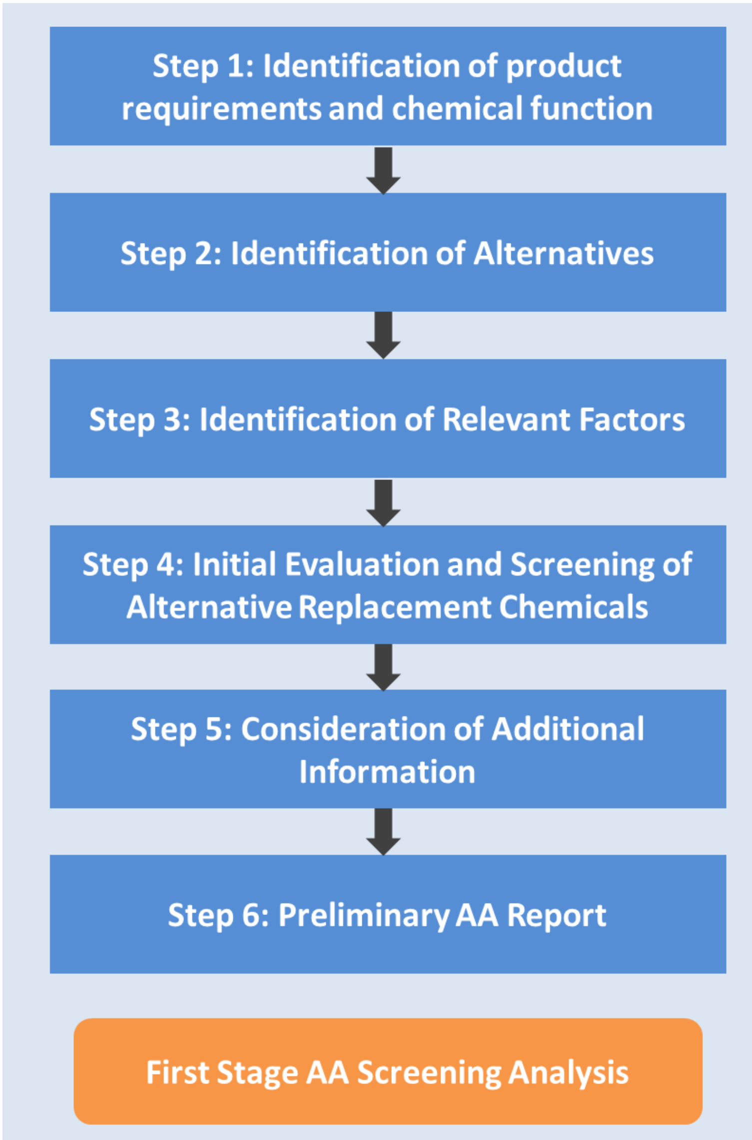
Preliminary AA Report
Abridged AA Report
Priority Product Notification
Notice of Compliance or Notice of Deficiency
Final Priority Product List
Final AA Report
DTSC review
60 days
120 days
180 days
60 days
12 months
1 year

Unique Characteristics of SCP AA

- Considers a broad range of alternatives, and **does not limit alternatives to only chemical replacement.**
  - For example: alternatives to consider may include removal of the Chemical of Concern or redesign of a Priority Product or manufacturing process to reduce exposure to the Chemical of Concern or adverse impacts.
- Covers comprehensive adverse impacts and **multimedia life cycle impacts.**
- Evaluates both external and internal cost impacts.
- **Does not mandate** responsible entities generate **new data** during the AA process.

From AA Guide p12

First vs. Second Stage



First vs. Second Stage

Step 1: Identification of product requirements and chemical function

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Step 2: Identification of Alternatives

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Step 3: Identification of Relevant Factors

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Step 4: Initial Evaluation and Screening of Alternative Replacement Chemicals

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Step 5: Consideration of Additional Information

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Step 6: Preliminary AA Report

First Stage AA Screening Analysis

Step 1: Identification of Relevant Factors

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Step 2: Comparison of the Priority Products and Alternatives

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Step 3: Consideration of Additional Information

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Step 4: Alternatives Selection Decision

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Step 5: Final AA Report

Second Stage AA Screening Analysis

What's the relevance of LCA to AA?

Relevance of Life Cycle in AA

- "The SCP approach requires an Alternatives Analysis* (AA) that considers important impacts of the product **throughout its life cycle** and follows up with specific actions to make the product safer."

** In the Safer Consumer Product regulations, the term "Alternatives Analysis (AA)" intentionally differentiates this effort from the practice of "Alternatives Assessment" which may only entail a chemical hazard evaluation and comparison or may include a breadth of considerations but not be as comprehensive as the analysis required by the regulations.*

From AA Guide p2

Relevance of Life Cycle in AA

- "Although the concept of Life Cycle Assessment (LCA) is briefly described here, it is important to note that a **LCA is not required** to conduct an AA. An approach that follows the LCA method is one way to quantify and assess impacts. **Any approach** which considers the impacts associated with the **full life cycle of the product** may be applied, such as those discussed in Chapter 4."

- "Responsible entities must consider the **full life cycle of the product** when assessing its impacts."

From AA Guide p80, 81

Adverse Impacts Throughout the Life Cycle Segments

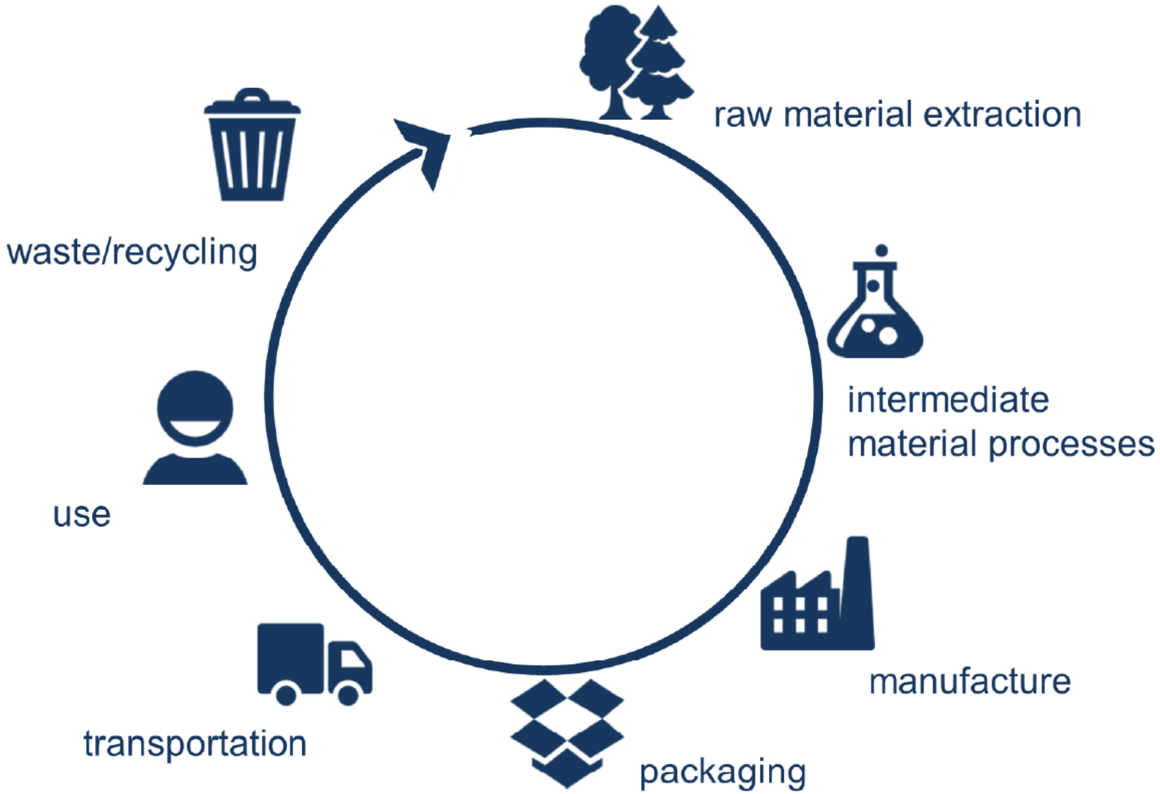
Table 3-1 Summary of Potential Factors Requiring Consideration for a Two-Stage AA

FIRST AND SECOND STAGE AA	
Adverse Impacts and Multimedia Life Cycle Impacts	
• Adverse environmental impacts • Adverse public health impacts • Adverse waste and end-of-life effects • Environmental fate • Materials and resource consumption impacts	• Physical chemical hazards • Physicochemical properties • Associated exposure pathways and life cycle segments
SECOND STAGE AA	
Product Function and Performance	**Economic Impacts**
• Principal manufacturer-intended uses or applications • Functional and performance attributes, and relative function and performance • Applicable legal requirements • Useful life of the product • Whether an alternative exists that is functionally acceptable, technically feasible, and economically feasible	• Public health and environmental costs • Costs to governmental agencies and non-profit organizations that manage waste, oversee environmental cleanup and restoration efforts, and/or are charged with protecting natural resources, water quality, and wildlife • Internal cost impacts

From AA Guide p30

Life Cycle Thinking (recap)

Life Cycle Segments



Cradle-to-Gate

Cradle-to-Grave

Well-to-wheel

Jordan Chamberlain, Kristen Magnuson, Carolin Meier , Yu Yu, Arturo Keller, Incorporating life cycle screening into Alternatives Analysis.

Life Cycle Segments

- In AA, “life cycle” means the sum of all the following activities:
  - raw materials extraction
  - resource inputs and other resource consumption
  - intermediate materials processes
  - manufacture
  - packaging
  - transportation
  - distribution
  - use
  - operation and maintenance
  - waste generation and management
  - reuse and recycling
  - end-of-life disposal

Why Life Cycle Thinking

- Understand the energy, resources, and environmental impacts arising from different life cycle segments.
- Understand the trade-offs (among life cycle segments and impact categories).
- Find opportunities to improve a product's environmental performance.
- **Identify potential regrets** that may arise from a change to a product system.

How can LCA help AA?

- First Stage
- Second Stage

First Stage (Step 1 & 2)

Step 1: Identification of product requirements and chemical function

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Step 2: Identification of Alternatives

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Step 3: Identification of Relevant Factors

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Step 4: Initial Evaluation and Screening of Alternative Replacement Chemicals

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Step 5: Consideration of Additional Information

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Step 6: Preliminary AA Report

First Stage AA Screening Analysis

LCA Knowledge

- **Functional Unit**

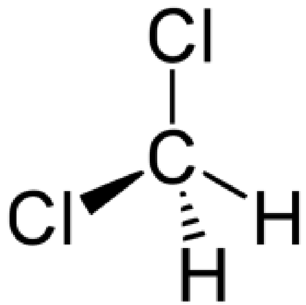
What is Functional Equivalency?

- **Functional Unit**
  - In defining the scope of an LCA study, a clear statement on the specification of the functions (performance characteristics) of the product shall be made.
  - The functional unit defines the quantification of these identified functions. The functional unit shall be consistent with the goal and scope of the study.
  - One of the primary purposes of a functional unit is to provide a reference to which the input and output data are normalized (in a mathematical sense). Therefore the functional unit shall be clearly defined and measurable.

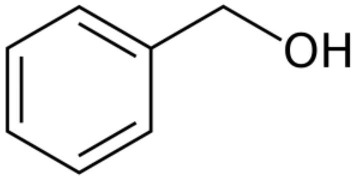
Functional Unit

Paint Stripper Alternatives

- Methylene Chloride



- Benzyl Alcohol



- Functional Unit: to strip the paint on the same area of wall :
  - MC : BA = 1 : 0.83

Jordan Chamberlain, Arturo Keller, etc., Safer consumer products alternatives analysis development.
https://www.edf.org/health/banning-methylene-chloride-paint-strippers

First Stage (Step 3)

Step 1: Identification of product requirements and chemical function

Step 2: Identification of Alternatives

Step 3: Identification of Relevant Factors

Step 4: Initial Evaluation and Screening of Alternative Replacement Chemicals

Step 5: Consideration of Additional Information

Step 6: Preliminary AA Report

First Stage AA Screening Analysis

LCA Knowledge

- Life Cycle Segments
- Life Cycle Inventory (LCI)

First Stage Step 3
1. Life cycle segments

Determination of Relevance

- **Determination of relevance:** A factor, in conjunction with its associated exposure pathways and life cycle segments, is relevant:
  - If the factor makes a **material contribution** to one or more adverse public health impacts, adverse environmental impacts, adverse waste and end-of-life effects, or materials and resource consumption impacts associated with the **Priority Product** and/or one or more alternatives under consideration; and
  - There is a **material difference** in the factor's contribution to impacts between the Priority Product and one or more alternative(s) under consideration and/or between two or more alternatives.

From AA Guide p29

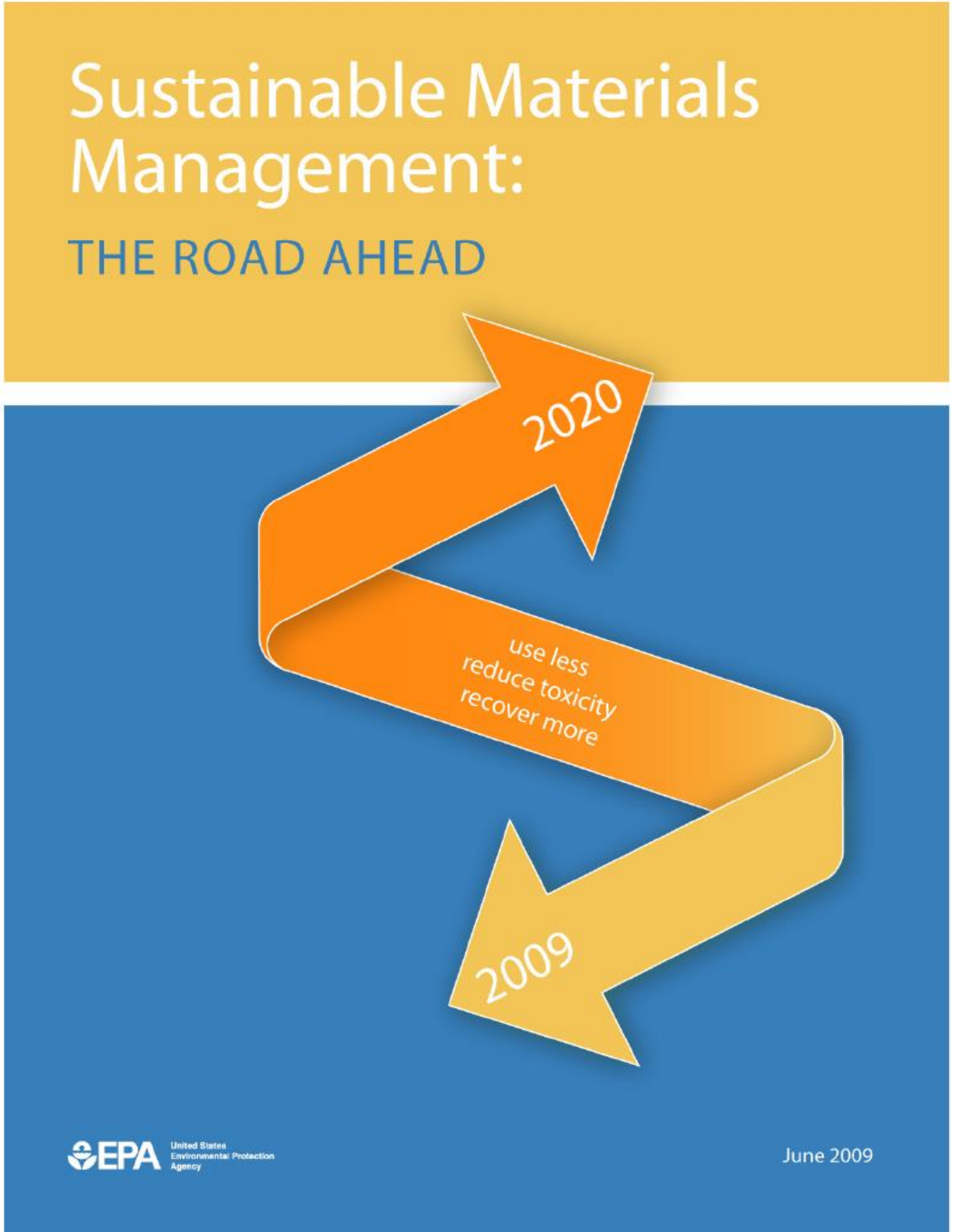

Sustainable Materials Management:
THE ROAD AHEAD
2020
use less
reduce toxicity
recover more
2009
EPA United States Environmental Protection Agency
June 2009

Table 1: Summary of Top-Ranked Materials, Products, and Services

	Material, Product, or Service	Final Rank			Environmental Aspects Significantly[1] Contributing to Final Rank		
		DI	IC	FC	Direct Impact/Resource Use/Waste Perspective	Intermediate Consumption Perspective	Final Consumption Perspective
Food Products & Services	Dairy farm products	19	–	–	LUC		
	Poultry and eggs	20	–	–	LUC		
	Meat animals	6	6	–	LUC	LUC, FAETP, TETP, EP	
	Food grains	13	–	–	LUC, EP		
	Feed grains	9	15	–	LUC, FAETP, TETP, EP, MU	ADP, LUC, FAETP, TETP, EP	
	Miscellaneous crops	16	–	–	FAETP, TETP, EP		
	Meat packing plants	–	11	7		LUC, FAETP, TETP, EP	LUC, FAETP, TETP
	Poultry slaughtering and processing	–	–	17			LUC,
	Eating and drinking places	–	16	5		LUC, GWP, FAETP, TETP, POCP, EP	LUC, GWP, ODP, HTP, FAETP, MAETP, TETP, FSETP, MSETP, POCP, AP, EP, MU, MW, EU
	Food preparations, n.e.c.	–	–	19			FAETP,TETP,EP
	Fluid milk	–	–	20			LUC
Textiles	Cotton	2	2	–	FAETP, TETP, EP	FAETP, TETP, EP	
	Apparel made from purchased materials	–	13	2		FAETP, TETP, EP	ODP, HTP, FAETP, TETP, MSETP, EP
	Broadwoven fabric mills and fabric finishing plants	–	10	–		FAETP, TETP, EP	
Nonrenewable Organics	Coal	5	9	–	ADP, MU, MW	ADP, MU, MW	
	Crude petroleum and natural gas	4	4	–	ADP, GWP, POCP	ADP, GWP, POCP, AP, EP	
	Industrial inorganic and organic chemicals	3	3	–	ODP, HTP, MSETP, MW	ODP, HTP, MSETP, POCP, EP, MW	
	Petroleum refining	8	5	3	MU, MW	ADP, GWP, POCP, AP, EP, MU, MW	ADP, GWP, ODP, POCP, AP, EP, MU, MW
	Electric services (utilities)	1	1	1	GWP, HTP, MAETP, FSETP, POCP, AP, EP, WU, EU	ADP, GWP, HTP, MAETP, FSETP, POCP, AP, EP, MU, MW, WU, EU	ADP, GWP, HTP, MAETP, FSETP, POCP, AP, EP, MU, MW, WU, EU
	Natural gas distribution	15	14	12	MU, MW	ADP, MU, MW	ADP, MW
Metals	Blast furnaces and steel mills	–	17	–		GWP, HTP, POCP, MW, EU	
	Primary aluminum	18	20	–	ODP, HTP, MAETP, FSEPT, MSEPT	ODP, HTP, MAETP, FSETP, MSETP	
	Motor vehicles and passenger car bodies	–	12	4		GWP, ODP, HTP, MAETP, FSETP, MSETP, POCP, EP, EU	ADP, GWP, ODP, HTP, FAETP, MAETP, TETP, FSETP, MSETP, POCP, AP, EP, MW, EU

Material Contribution vs. Material Difference

- **Material contribution:** relating to a factor that is both meaningful and consequential to an observed outcome or impact.

- **Material difference:** relating to a factor's contribution to an observed impact that is both meaningful and consequential to the comparison of alternatives.

From AA Guide p30

Identify Relevant Factors

Adverse Impacts

- What are the adverse impacts?

Life Cycle Segments

- What are the relevant life cycle segments?

Relevant Factors

- What are the relevant factors identified?

Example Chemical Discussion

Adverse Environmental Impacts

Adverse Public Health Impacts

Adverse Waste and End-of-life Effects

Environmental Fate

Materials and Resource Consumption

Physical Chemical Hazards

Physicochemical Properties

TABLE 3-1B ADVERSE IMPACTS

Factor Main Category	Factor Sub-category	Factors
Adverse impacts and multimedia life cycle impacts	Adverse public health impacts[18]	Carcinogenicity
		Developmental toxicity
		Reproductive toxicity
		Cardiovascular toxicity
		Dermatotoxicity
		Endocrine toxicity
		Epigenetic toxicity
		Genotoxicity
		Hematotoxicity
		Hepatotoxicity and digestive system toxicity
		Immunotoxicity
		Musculoskeletal toxicity
		Nephrotoxicity and other urinary system toxicity
		Neurodevelopmental toxicity
		Neurotoxicity
		Ocular toxicity
		Ototoxicity
		Reactivity in biological systems
		Respiratory toxicity
		Exceedance of an enforceable California or federal regulatory standard relating to the public health
	Adverse waste and end-of-life effects[19]	Volume or mass generated
		Any special handling needed
		Effects on solid waste and wastewater disposal and treatment
		Discharge to storm drains or sewer adversely affecting wastewater treatment facilities
		Release into the environment

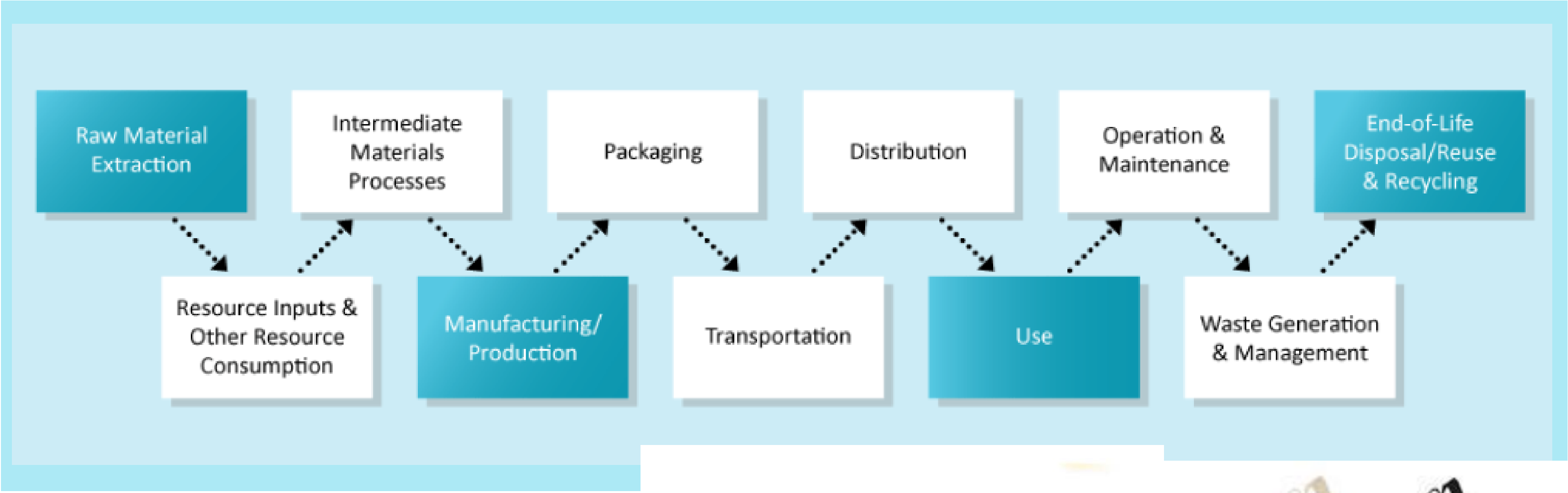
From AA Guide p170

How to Identify Relevant Segments?

- What life cycle segments associated with adverse impacts and exposures are identified in the Priority Product profile?
- What life cycle segments will be **significantly different** given a switch to an alternative?
- How does the Priority Product **compare** to alternatives with regard to materials and energy consumption **for each life cycle segment**?
- Can additional or different releases or exposures to humans or the environment occur during any life cycle segment by implementing alternatives?
- Will alternatives affect waste generation or the ways the product would be reused, recycled, or disposed?

From AA Guide p35

Identify Relevant Life Cycle Segments



from AA Guide p85

- Presenting the findings

Example 3-2 (Continued): Comparison of Relevant Life Cycle Segment

Priority Product	Life Cycle Segment	Alternative A	Alternative B	Alternative C
• A small amount of post-industrial recycled content • PBTs, CMRs during petroleum extraction and refining	Raw Materials Extraction	• High post-consumer recycled content (may be toxic) • PBTs, CMRs during petroleum extraction and refining	• Limited post-consumer recycled content • PBTs, CMRs during petroleum extraction and refining	• High renewable content/post-industrial recycled content • Toxic pesticides (may be eliminated) • Eutrophication
• PBTs • CMRs • Heavy metals • Endocrine disruptors • VOCs and solvents	Manu-facturing/ Production	• PBTs (may be designed out) • CMRs • Heavy metals	• No identified PBTs • Few CMRs (may be eliminated) • Lack of emission data	• No PBTs • CMRs (may be eliminated) • Dust
• Flame retardants • Phthalates • VOCs • Pigments	Use	• Flame retardants • Heavy metals • VOCs • Pigments	• One problematic metal (aquatic toxicant) • VOCs • Pigments	• No heavy metals • VOCs and odors (may be reduced) • Pigments
• PBTs • Post – consumer recycling challenging	End-of-Life Disposal and Reuse/ Recycling	• Lack of studies • Limited recycling	• No identified PBTs (except one problematic decomposition product) • Down-grade recycling	• No identified PBTs • Pilot composting program available

This diagram shows the qualitative differences among the Product and the three alternatives; these differences make the four life cycle segments potentially relevant when comparing the alternatives to the Product.

*Adapted from: Tom Lent, Julie Silas, and Jim Valette. Resilient Flooring & Chemical Hazards: A Comparative Analysis of Vinyl and Other Alternatives for Health Care. Healthy Building Network, April, 2009.

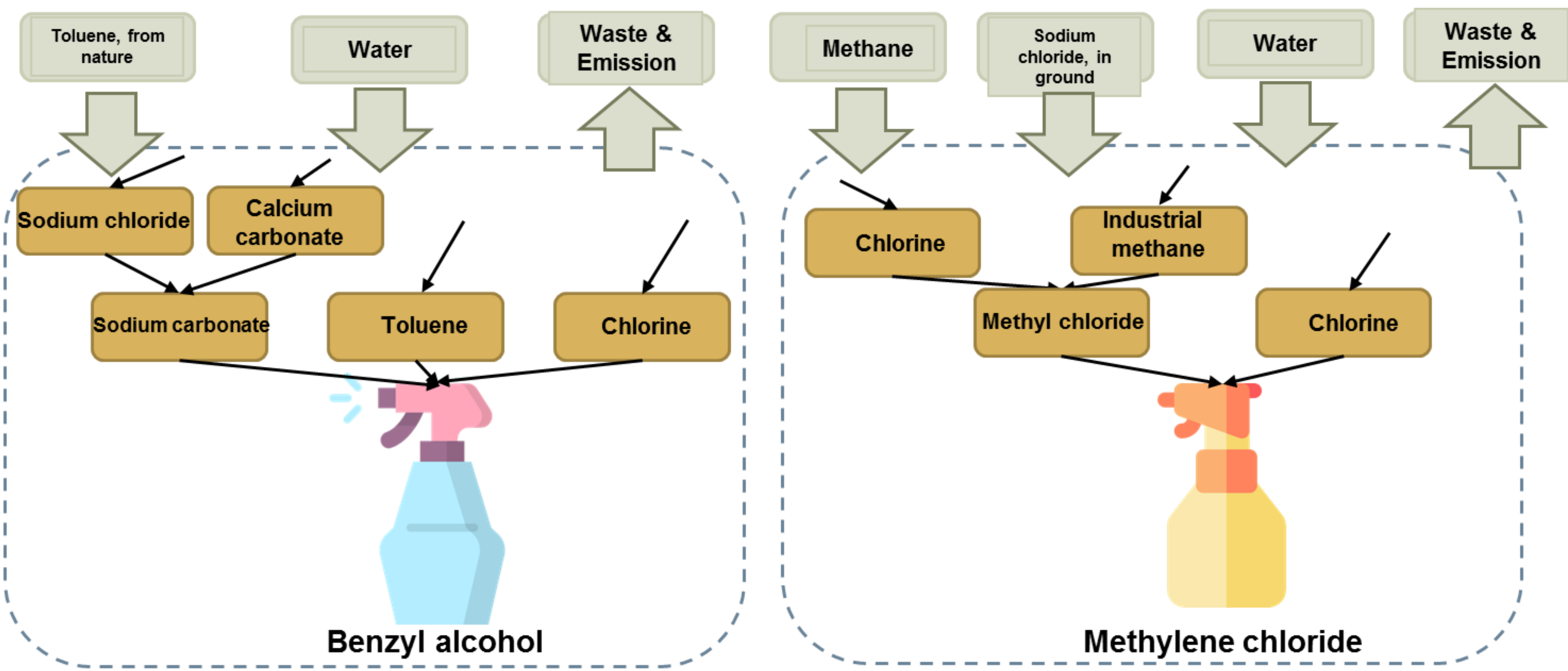
from AA Guide p37

First Stage Step 3
2. Life Cycle Inventory

Life Cycle Inventory Analysis

- Compilation and quantification of inputs and outputs, for a given product throughout its life cycle.
- Can help to identify adverse impacts/relevant factors.

Example of Chemical Production Phase



Product: Finished Cold Rolled Coil, BF Route, Worldwide average, 1kg

Product: Finished Cold Rolled Coil, BF Route, Worldwide average, 1kg
Issued by: IISI
Date issued: August 2002
Date of data: 1999-2000

	Major Articles*	Unit	Average (26 sites)
Inputs:	(r) Coal (in ground)	kg	0.789481
	(r) Dolomite ($CaCO_3 \cdot MgCO_3$, in ground)kg	0.0290661	
	(r) Iron (Fe)	kg	1.91427
	(r) Limestone ($CaCO_3$, in ground)	kg	-0.0110614
	(r) Natural Gas (in ground)	kg	0.0624542
	(r) Oil (in ground)	kg	0.0463004
	(r) Zinc (Zn)	kg	-2.48E-05
	Ferrous Scrap (net)	kg	0.09144213
	Water Used (total)	litre	23.1882
Outputs:	(a) Cadmium (Cd)	g	7.00E-05
	(a) Carbon Dioxide (CO_2)	g	2616.11
	(a) Carbon Monoxide (CO)	g	31.9049
	(a) Chromium (Total)	g	3.91E-03
	(a) Dioxins (unspecified, as TEq))	g	2.06E-08
	(a) Hydrogen Chloride (HCl)	g	0.086121
	(a) Hydrogen Sulfide (H_2S)	g	0.0843961
	(a) Lead (Pb)	g	0.00380944
	(a) Mercury (Hg)	g	6.87E-05
	(a) Methane (CH_4)	g	1.00906
	(a) Nitrogen Oxides (NO_x as NO_2)	g	3.30931
	(a) Nitrous Oxide (N_2O)	g	0.135275
	(a) Particulates (Total)	g	2.013858827
	(a) Sulfur Oxides (SO_x as SO_2)	g	3.22123
	(a) VOC (except methane)	g	0.153512
	(a) Zinc (Zn)	g	0.00367601
	(w) Ammonia (NH_4^+, NH_3, as N)	g	0.0868194
	(w) Cadmium (Cd^{2+})	g	7.47E-05
	(w) Chromium (Total)	g	1.21E-04
	(w) COD (Chemical Oxygen Demand)	g	0.302357
	(w) Iron (Fe^{2+}, Fe^{3+})	g	0.0417901
	(w) Lead (Pb^{2+}, Pb^{4+})	g	2.73E-05
	(w) Nickel (Ni^{2+}, Ni^{3+})	g	0.000234569
	(w) Nitrogenous Matter (unspecified, as N)	g	0.0264328
	(w) Phosphorous Matter (unspecified, as P)	g	0.0033978
	(w) Suspended Matter (unspecified)	g	0.250121
	(w) Zinc (Zn^{2+})	g	0.0021733
	Non-allocated by-products (see table below)	kg	0.0900452
	Waste (total)	kg	1.75255
Energy Reminders:	E Feedstock Energy	MJ	-0.213737
	E Fuel Energy	MJ	31.1173
	E Non-renewable Energy	MJ	30.3653
	E Renewable Energy	MJ	0.392903
	E Total Primary Energy	MJ	30.9034

The Results of An LCI

- Usually a long list of elementary flows.
- Difficult to understand, interpret or compare from an environmental impact point of view.

First Stage (Step 4&5)

Step 1: Identification of product requirements and chemical function

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Step 2: Identification of Alternatives

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Step 3: Identification of Relevant Factors

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Step 4: Initial Evaluation and Screening of Alternative Replacement Chemicals

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Step 5: Consideration of Additional Information

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Step 6: Preliminary AA Report

First Stage AA Screening Analysis

LCA Knowledge

- Interpretation

Table 5-1 Relevant Life Cycle Segments & Factors

Relevant Life Cycle Segment	Relevant Factors or Impacts	Priority Product	ALT 1	ALT 2	ALT 3-10
Raw Material Extraction	Environmental Impacts	H	○	○	○
	Public Health Impacts	H	○	○	○
	Waste and End-of life				
	Environmental Fate	H	M	M	
	Materials & Resource Consumption Impacts				
	Physical chemical hazards				
	Physiochemical properties				
Intermediate Process	Environmental Impacts				
	Public Health Impacts				
	Waste and End-of life				
	Environmental Fate				
	Materials & Resource Consumption Impacts	M	H	L	H
	Physical chemical hazards				
	Physiochemical properties				
MFR	Environmental Impacts	H			
	Public Health Impacts	M			
	Waste and End-of life				
	Environmental Fate	H			
	Materials & Resource Consumption Impacts				
	Physical chemical hazards				
	Physiochemical properties				
Packaging & Transportation		⊘	⊘	⊘	⊘
Distribution		⊘	⊘	⊘	⊘
Use	Environmental Impacts	H	L	H	M
	Public Health Impacts	H	M	M	M
	Waste and End-of life				
	Environmental Fate	M	H	L	H
	Materials & Resource Consumption Impacts				
	Physical chemical hazards				
	Physiochemical properties				
Operation & Maintenance		⊘	⊘	⊘	⊘
Reuse & Recycling	Environmental Impacts	H	○	M	
	Public Health Impacts	L	○	L	
	Waste and End-of-life	H		M	
	Environmental Fate	H		M	
	Materials & Resource Consumption Impacts				
	Physical chemical hazards				
	Physiochemical properties				
End-of-Life		⊘	⊘	⊘	⊘

H = High Impact observed
M = Medium Impact observed
L = Low Impact observed
● - Data not available (impact not quantifiable)
○ - Data not available
⊘ - Not Applicable

From AA Guide p59

Inferior Alternatives

- Exhibits a greater adverse impact to air quality, human health and ecological endpoints, soil quality, or water quality.
- Exhibits a greater impact from toxicological hazard traits.
- Generates more material waste or waste byproducts **during its life cycle.**
- Is more persistent in the environment, as determined by its environmental fate characteristics.
- Creates a greater consumption burden on society by using a larger volume or amount of renewable and nonrenewable resources **throughout its life cycle.**
- Poses a greater handling danger, as indicated by its physicochemical hazards.
- Poses a greater reactive or flammability hazard, as indicated by its physicochemical properties.

Modified from AA Guide p75

Second Stage AA

Second Stage (Step 1 & 2)

Step 1: Identification of Relevant Factors

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Step 2: Comparison of the Priority Products and Alternatives

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Step 3: Consideration of Additional Information

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Step 4: Alternatives Selection Decision

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Step 5: Final AA Report

Second Stage AA Screening Analysis

LCA Knowledge

- Life Cycle Inventory (LCI)
- Life Cycle Impact Assessment (LCIA)

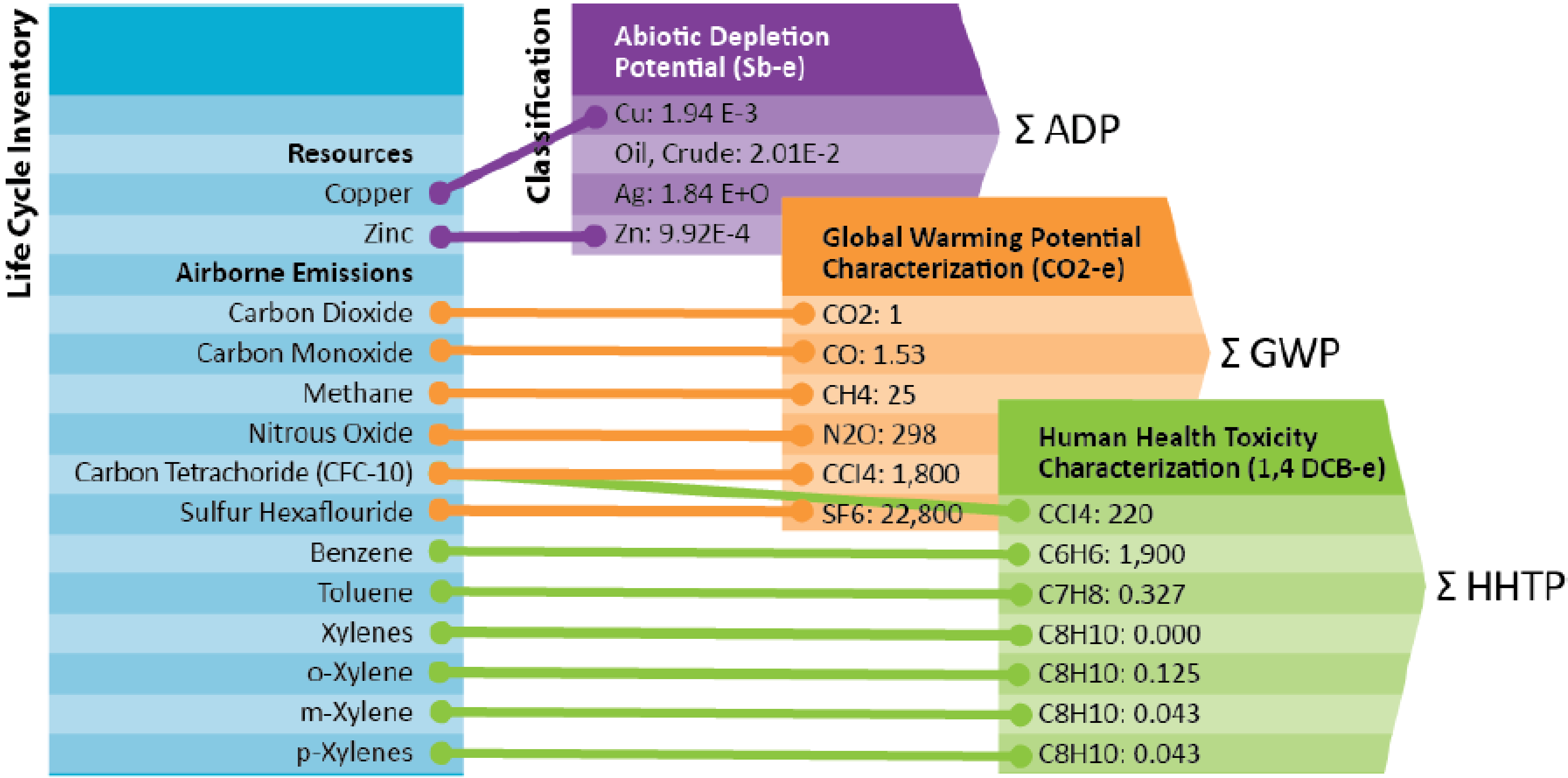


Figure 7-2 **Classification** **and** **Characterization of LCI Data** (Adapted from: Environmental Life Cycle Assessment – Measuring the Environmental Performance of Products. American Center for Life Cycle Assessment. 2014)

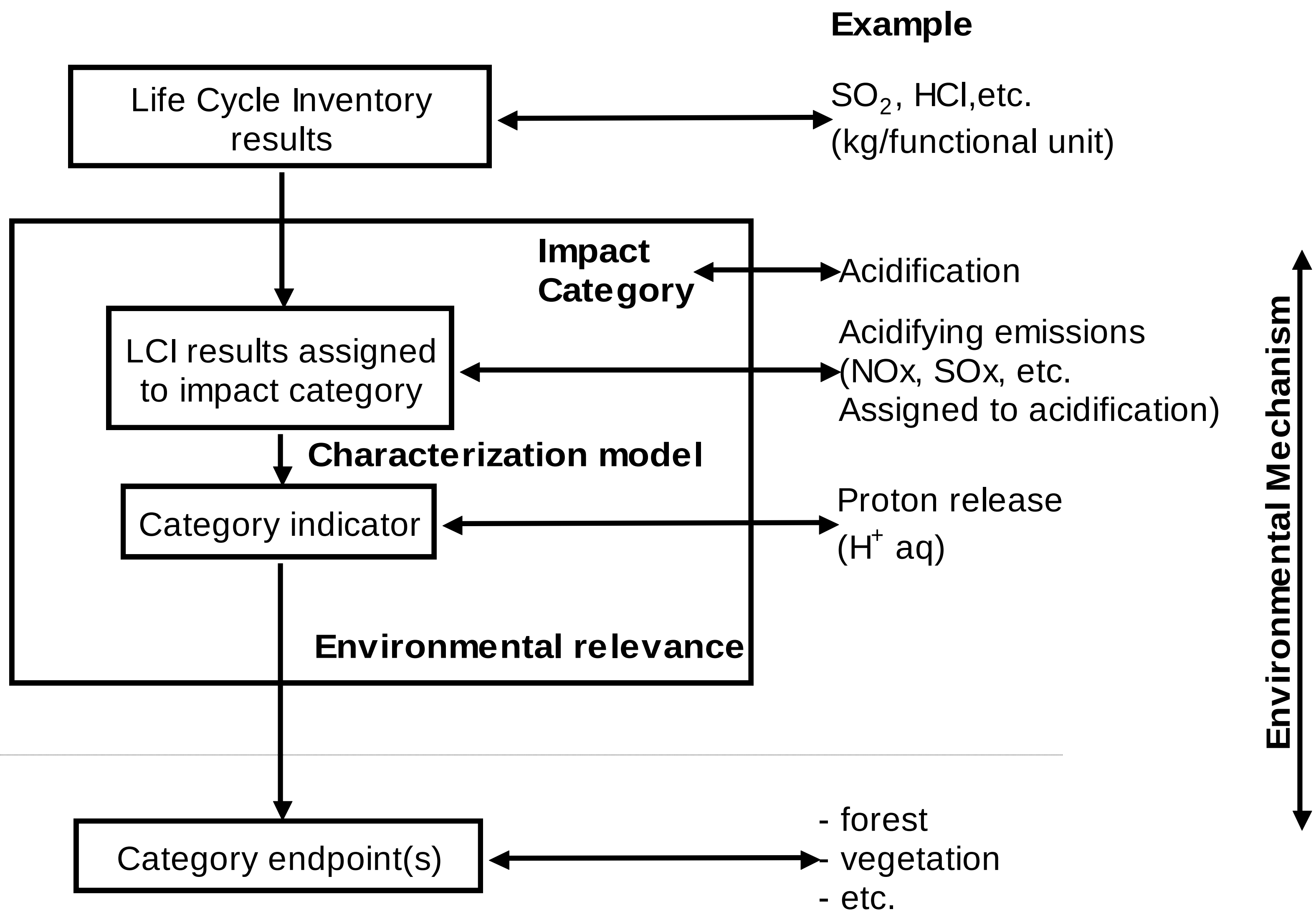
What is Characterization?

- Characterization translates different stressors into the same unit based on their potential harm to one or more “area of protection”
  - Ecosystem health
  - Human health
  - Natural resources
- Requires modeling of environmental mechanisms
  - Fate & transport (e.g. soil→plants→humans)
  - Effect (e.g. toxicity potential of substance)
  - Exposure
- Midpoints vs. Endpoints

Environmental Impact Category

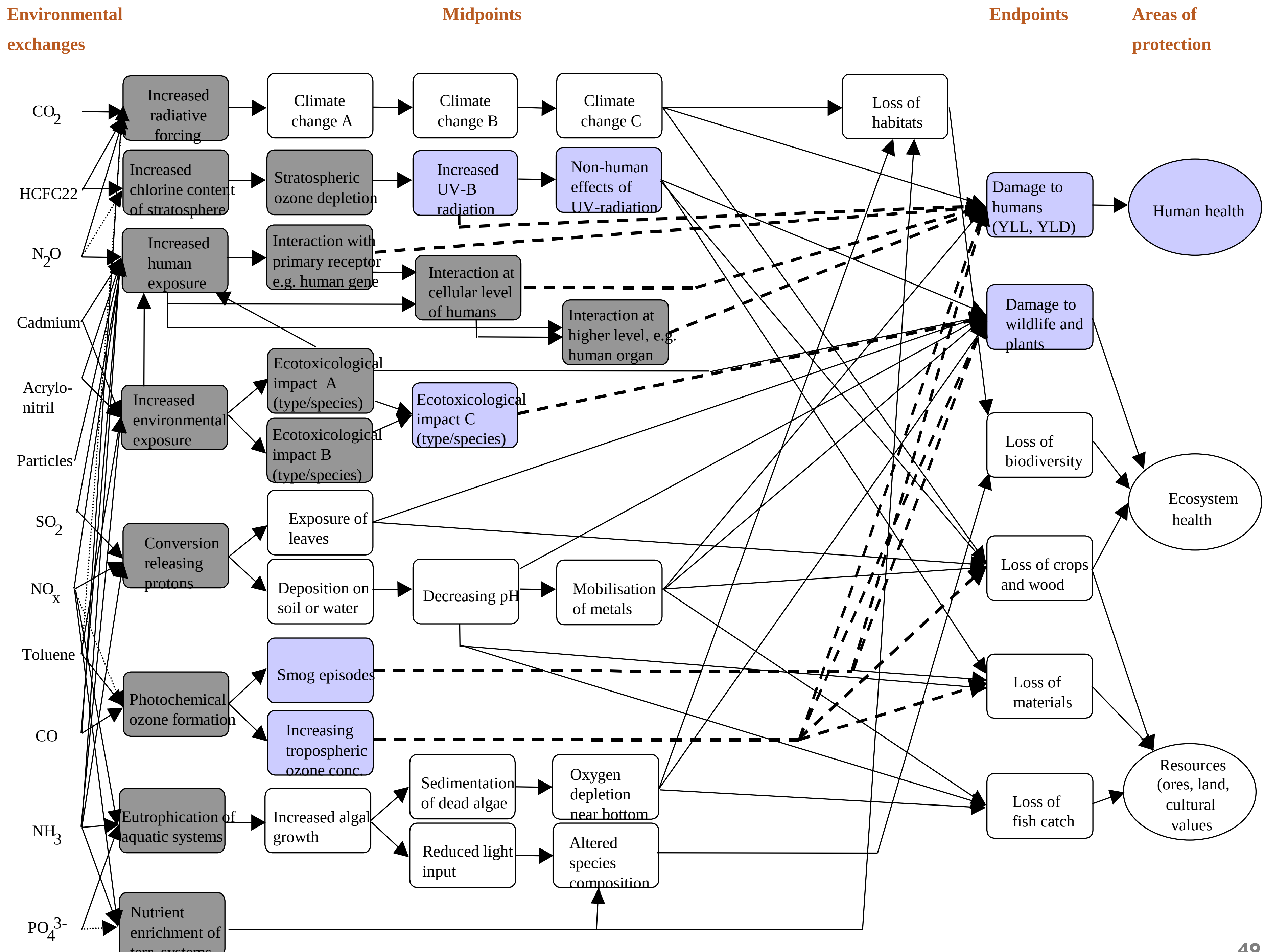
- In short, just “Impact Category”
  - Class representing environmental issues of concern to which LCI results may be assigned (ISO 14042).
  - More intuitively, an impact category is a group of environmental impacts that can be represented by a commensurate indicator, such as Global Warming Potential (GWP).

Environmental Mechanism



Environmental Mechanism

- Hg and Pb (or CO_2 and CH_4) emissions to air from a coal power plant.
  - Impact category?
  - Category endpoint?
  - Environmental mechanism?
  - Category indicator?


Environmental exchanges
Midpoints
Endpoints
Areas of protection
CO_2
HCFC22
N_2O
Cadmium
Acrylo-nitril
Particles
SO_2
NO_x
Toluene
CO
NH_3
PO_4^{3-}
Increased radiative forcing
Increased chlorine content of stratosphere
Increased human exposure
Increased environmental exposure
Conversion releasing protons
Photochemical ozone formation
Eutrophication of aquatic systems
Nutrient enrichment of terr. systems
Climate change A
Climate change B
Climate change C
Stratospheric ozone depletion
Increased UV-B radiation
Non-human effects of UV-radiation
Interaction with primary receptor e.g. human gene
Interaction at cellular level of humans
Interaction at higher level, e.g. human organ
Ecotoxicological impact A (type/species)
Ecotoxicological impact B (type/species)
Ecotoxicological impact C (type/species)
Exposure of leaves
Deposition on soil or water
Decreasing pH
Mobilisation of metals
Smog episodes
Increasing tropospheric ozone conc.
Increased algal growth
Sedimentation of dead algae
Reduced light input
Oxygen depletion near bottom
Altered species composition
Loss of habitats
Damage to humans (YLL, YLD)
Damage to wildlife and plants
Loss of biodiversity
Loss of crops and wood
Loss of materials
Loss of fish catch
Human health
Ecosystem health
Resources (ores, land, cultural values)

Calculation of Characterized Results

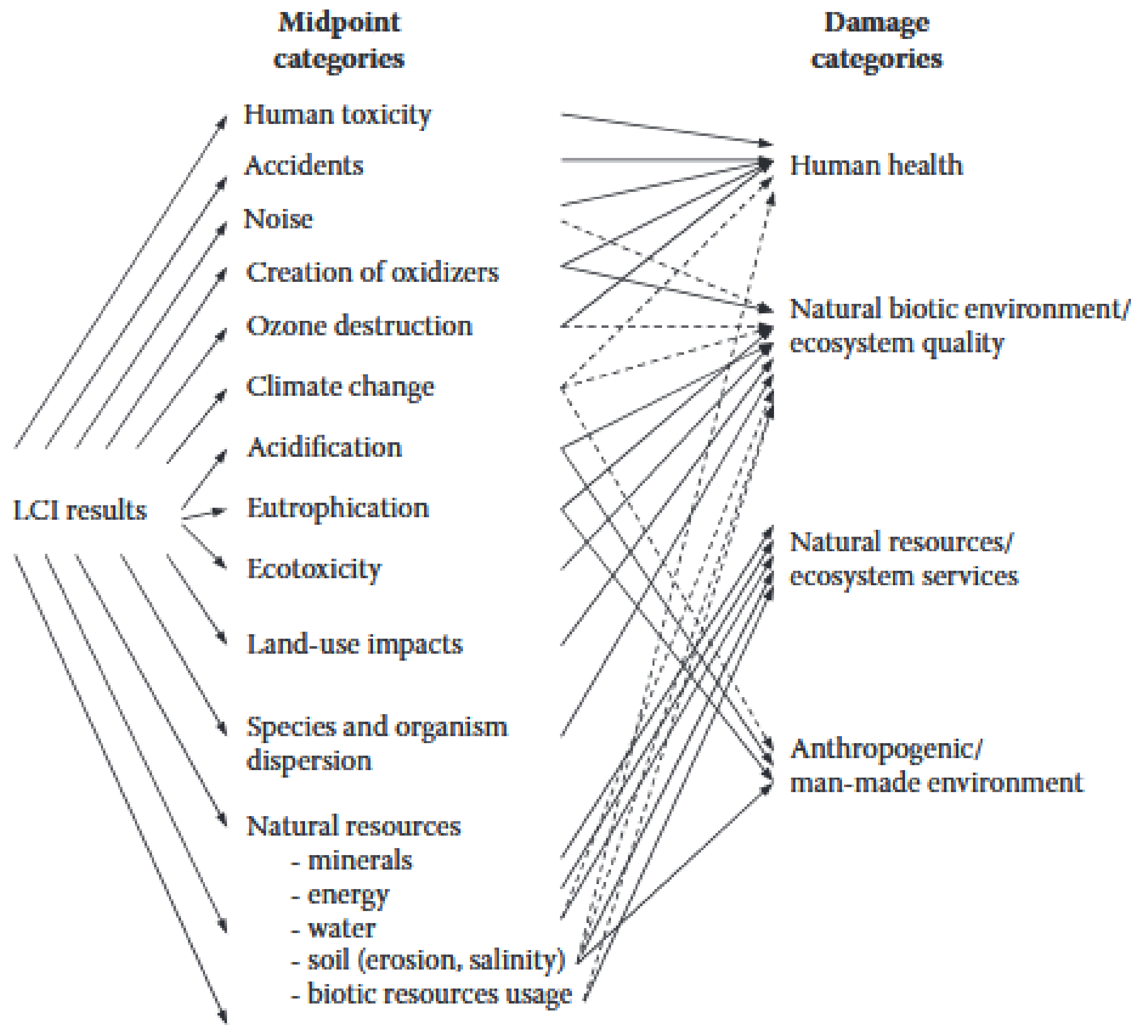
- $c_{ij} = f_{ij}m_j$
  - c_{ij} = characterized result of *j* on impact category *i*
  - m_j = inventory result of environmental intervention *j*
  - f_{ij} = characterization factor of *j* on impact category *I*

- Total Characterized result for impact category *i*

$$c_i = \sum_j f_{ij} m_j$$

$$\Leftrightarrow \mathbf{c} = \mathbf{Fm} \quad \text{(for all } i\text{)}$$

Life Cycle Impact Assessment



Environmental life cycle assessment. Boca Raton : CRC Press 2016. Jolliet Olivier Myriam Saadé-Sbeih; Shanna Shaked; Alexandre Jolliet; Pierre Crettaz.

Characterization

Substance	CAS.no.	Emission to air g	Emission to water g
2-hydroxy-ethanacrylate	816-61-0	0,0348	
4,4-methylenebis cyclohexylamine	1761-71-2	5,9E-02	
Ammonia	7664-81-7	3,7E-05	4,2E-05
Arsenic (As)	7440-38-2	2,0E-06	
Benzene	71-43-2 (cur	5,0E-02	
Lead (Pb)	7439-92-1	8,5E-06	
Butoxyethanol	111-76-2	6,6E-01	
Carbondioxide	124-38-9	2,6E+02	
Carbonmonoxide (CO)	630-08-0	1,9E-01	
Cadmium (Cd)	7440-46-9	2,2E-07	
Chlorine (Cl2)	7782-50-5	4,6E-04	
Chromium (Cr VI)	7440-47-3	5,3E-06	
Dicyclohexane methane	86-73-6	5,1E-02	
Nitrous oxide(N2O)	10024-97-2	1,7E-02	
2,4-Dinitrotoluene	121-14-2	9,5E-02	
HMDI	5124-30-1	7,5E-02	
Hydro carbons (electricity, stationary combustic	-	1,7E+00	
Hydrogen ions (H+)	-		1,0E-03
i-butanol	78-83-1	3,5E-02	
i-propanol	67-63-0	9,2E-01	
copper (Cu)	7740-50-8	1,8E-05	
Mercury(Hg)	7439-97-6	2,7E-06	
Methane	74-82-8	5,0E-03	
Methyl i-butyl ketone	108-10-1	5,7E-02	
Monoethyl amine	75-04-7		7,9E-06
Nickel (Ni)	7440-02-0	1,1E-05	
Nitrogen oxide (NOx)	10102-44-0	1,1E+00	
NMVOC, diesel engine (exhaust)	-	3,9E-02	
NMVOC, pow er plants (stationary combustion)	-	3,9E-03	
Ozone (O3)	10028-15-6	1,8E-03	
PAH	ikke specifik	2,4E-08	
Phenol	108-95-2		1,3E-05
Phosgene	75-44-5	1,4E-01	
Polyeter polyol	ikke specifik	1,6E-01	
1,2-propylenoxide	75-56-9	8,2E-02	
Nitric acid	7782-77-6 (c	8,5E-02	
Hydrochloric acid	7647-01-0 (c	1,9E-02	
Selenium (Se)	7782-49-2	2,6E-05	
Sulphur dioxide(SO2)	7446-09-5	1,3E+00	
Toluene	108-88-3	4,8E-02	
Toluene-2,4-diamine	95-80-7	7,9E-02	
Toluene diisocyanat (TDI)	26471-62-5	1,6E-01	
Total-N	-		2,6E-05
Triethylamine	121-44-8	1,6E-01	
Unspecified aldehydes	-	7,5E-04	
Uspecified organic compounds	-	1,5E-03	
Vanadium	7440-62-2	1,8E-04	
VOC, diesel engine (exhaust)	-	6,4E-05	
VOC, stationary combustion (coal fired)	-	4,0E-05	
VOC, stationary combustion (natural gas fired)	-	2,2E-03	
VOC, stationary combustion (oil fired)	-	1,4E-04	
Xylene	1330-20-7	1,4E-01	
Zinc (Zn)	7440-66-6	8,9E-05	

Global warming	174.000	kg CO_2-eq
Ozone depletion	0	kg CFC11-eq
Acidification	868	kg SO_2-eq
Photochemical ozone formation	200	kg C_2H_4-eq
Nutrient enrichment	3.576	kg NO_3^--eq
Human toxicity	$3{,}40 \cdot 10^{11}$	m^3 air
Ecotoxicity	$2{,}16 \cdot 10^{7}$	m^3 water
Land use	170	ha·yr
Volume waste	9.450	kg
Hazardous waste	248	kg

Hauschild, 2004

Typical Midpoint Impact Categories

Table 7-5 lists the typical midpoint impact categories examined with LCA along with the corresponding relevant factors required by the regulations.

Table 7-5 Typical Midpoint Impact Categories

Midpoint Impact Categories	SCP Regulations: Factors to Consider for Relevance
Global Warming Potential	Adverse air quality impacts/Greenhouse Gases
Ozone Depletion Potential	Adverse air quality impacts/Stratospheric ozone depletion substances
Photochemical Smog	Adverse air quality impacts/Tropospheric ozone forming compounds
Particulate Matter Emissions	Adverse air quality impacts/Particulate matter
Eutrophication	Adverse ecological impacts; Adverse water quality impacts
Acidification	Adverse ecological impacts
Ecotoxicity	Adverse ecological impacts
Human Health Effects	Adverse human health impacts
Resource Depletion	Materials and resource consumption impacts
Water Use	Materials and resource consumption impacts

From AA Guide p91

Second Stage (Step 3)

Step 1: Identification of Relevant Factors

↓

Step 2: Comparison of the Priority Products and Alternatives

↓

Step 3: Consideration of Additional Information

↓

Step 4: Alternatives Selection Decision

↓

Step 5: Final AA Report

Second Stage AA Screening Analysis

→

LCA Knowledge

- Life Cycle Cost
- Life Cycle Social Impacts

Second Stage (Step 4)

Step 1: Identification of Relevant Factors

⬇

Step 2: Comparison of the Priority Products and Alternatives

⬇

Step 3: Consideration of Additional Information

⬇

Step 4: Alternatives Selection Decision → **LCA Knowledge**
- **Weighting**
- **Normalization**

⬇

Step 5: Final AA Report

Second Stage AA Screening Analysis

Consideration of Trade-offs

"The AA process requires a comparison of a Priority Product with alternatives by analyzing a number of predefined factors. **Public health impacts, environmental impacts, life cycle processes, product function and requirements, and economics** are all evaluated in order to make a decision. The consideration of a variety of factors will result in various **trade-offs requiring value judgments.** The **challenge** is in handling a large amount of **complex information** in a consistent way."

From AA Guide p133

Decision Analysis

- "…even if the responsible entity does not deliberately apply weighting factors, a value judgment is still being made on their relative importance."

- Multi-criteria decision analysis (MCDA) common approaches:
  - Multi-attribute utility theory (MAUT) (optimization tool)
  - Outranking models

From AA Guide p137

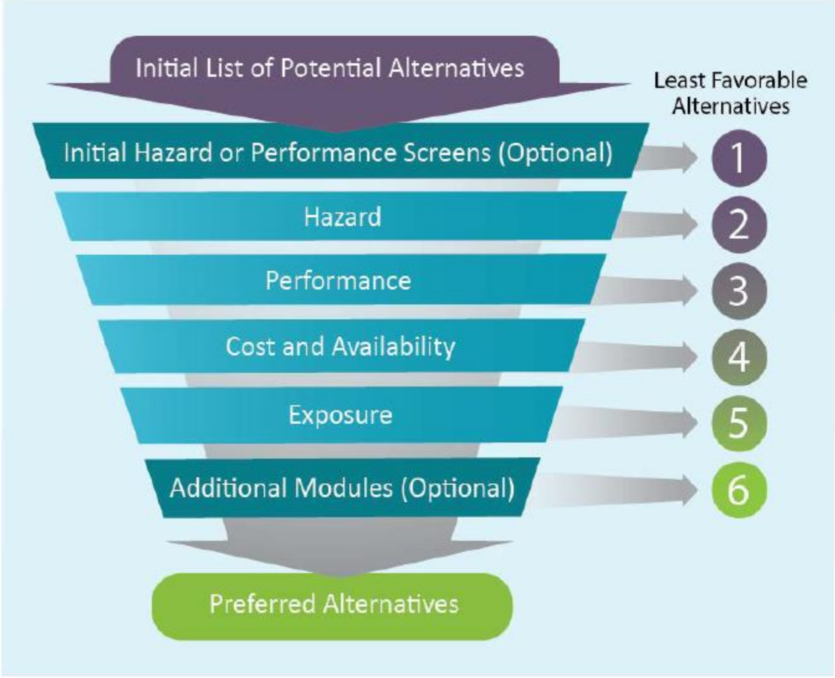


Figure 10-1 Sequential Framework[18]

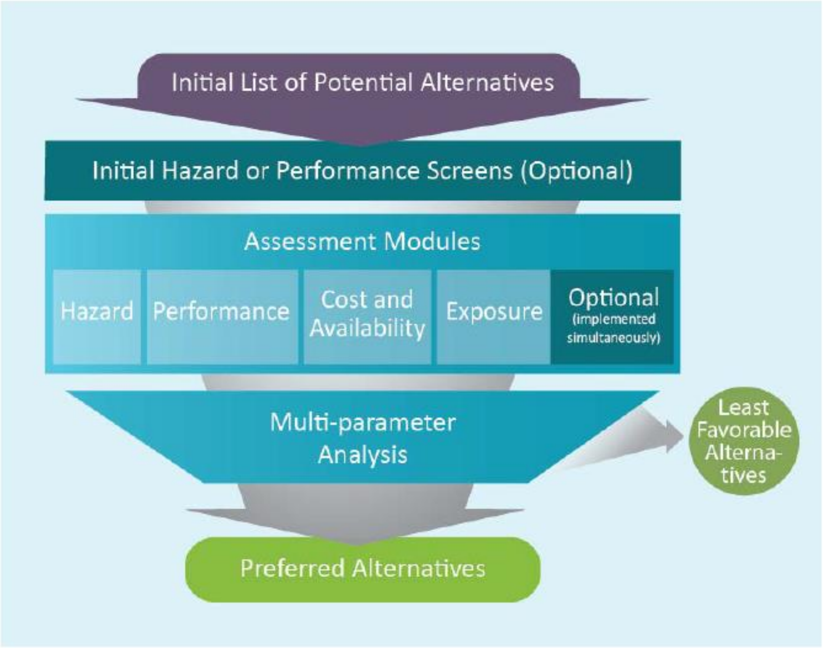


Figure 10-2 Simultaneous Framework[18]

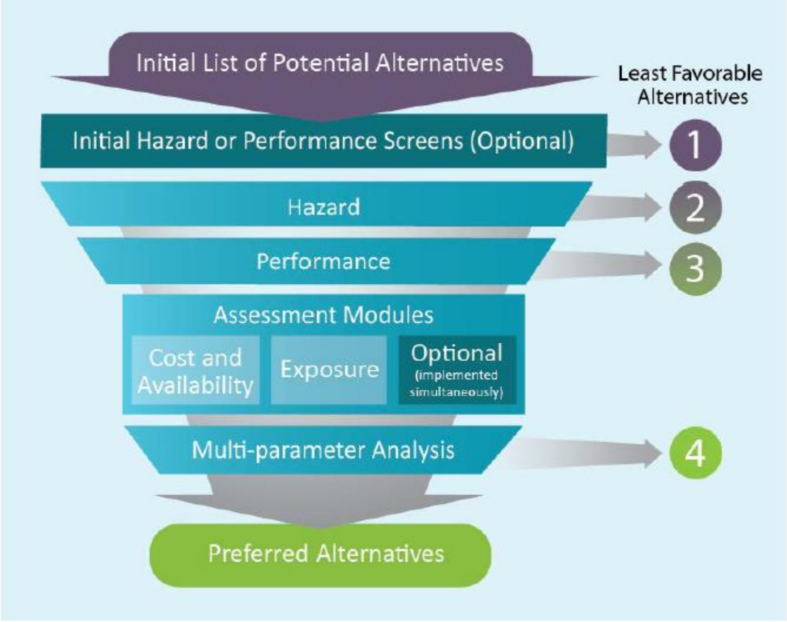


Figure 10-3 Hybrid Framework[18]

Table 10-1 provides a general discussion on the advantages and disadvantages of the three decision frameworks discussed above.

Table 10-1 Comparison of Decision Frameworks		
Decision Framework	**Pros**	**Cons**
Sequential Framework	• Establishes an evaluation hierarchy for the impacts which includes ranking the impacts by level of importance. • Compares alternatives using the evaluation hierarchy in a series of steps. • Filters out less desirable alternatives. • Does not require the use of a decision method.	• Does not establish weighting criteria for impacts. • Does not establish a ranking criteria for alternatives. • Does not allow consideration of trade-offs between impacts. • Requires assigning an order of importance to the impacts. • The evaluation hierarchy will vary since it is based on the responsible entity's values.
Simultaneous Framework	• Considers all or a set of impacts at once allowing for trade-offs (e.g., good performance on one attribute to offset less favorable performance on another attribute) • Establishes an evaluation hierarchy for impacts which includes: o Weighting criteria, o Trade-off criteria, o Ranking impacts by level of importance, and o Ranking criteria for alternatives.	• The evaluation hierarchy will vary since it is based on the responsible entity's values. • Requires establishing weighting criteria which can be resource- and time-consuming. • Requires the use of computerized calculations. • Requires the use of decision methods to evaluate trade-offs between impacts.
Hybrid Framework	• Combines parts of both Sequential and Simultaneous Frameworks. • Establishes an evaluation hierarchy for the impacts which includes: o Weighting criteria, o Trade-off criteria, o Ranking impacts by level of importance, and Ranking criteria for alternatives. • Uses the Sequential Framework to screen alternatives based on impacts deemed of high importance.	• The evaluation hierarchy will vary since it is based on the responsible entity's values. • Requires establishing weighting criteria which can be resource- and time-consuming, • Requires the use of computerized calculations. • Requires the use of decision methods to evaluate trade-offs between impacts.

From AA Guide p136

Normalization and Weighting

- Normalization and weighting help us understand the "magnitude and significance" of category indicator results.

- Normalization makes indicator results unit-less. Examples include:
  - Comparison to baseline or standard technology (percentage).
  - Normalized by total annual regional or global emissions.

Calculation of Normalized Results

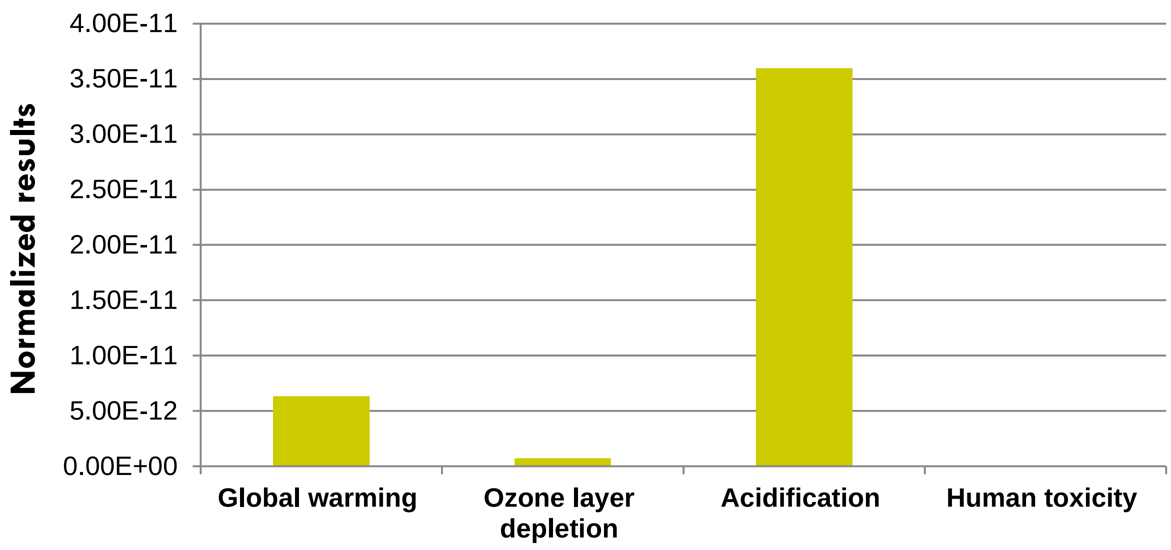
$$\text{Normalized result of impact category } i = \frac{c_i}{n_i}$$

- Calculate the normalization references based on the following information, and identify the impact by this product that is relatively the most significant among the impact categories considered.

Impact category	Unit	Characterized result	Normalization reference (world total)
Global warming	Kg CO2-equiv.	260	4.11E13
Ozone layer depletion	Kg CFC-11-equiv.	0.00014	1.92E8
Acidification	Kg SO2-equiv.	8.6	2.39E11
Human toxicity	kg 1,4-dichlorobenzene eq.	0.045	3.51E13

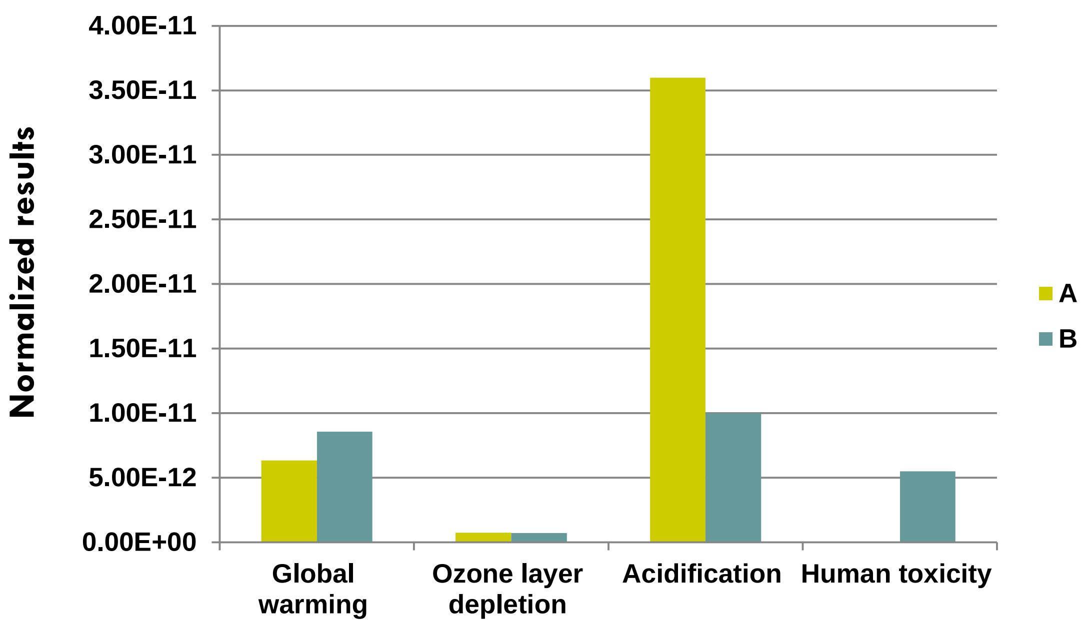
Interpretation of Normalized Results

Impact category	Unit	Characterized result	Normalization reference (world total)	Normalized results
Global warming	Kg CO2-equiv.	260	4.11E13	6.33E-12
Ozone layer depletion	Kg CFC-11-equiv.	0.00014	1.92E8	7.29E-13
Acidification	Kg SO2-equiv.	8.6	2.39E11	3.60E-11
Human toxicity	kg 1,4-dichlorobenzene eq.	0.045	3.51E13	1.28E-15



Interpretation of Normalized Results

- But not all environmental impact categories are equally important.
- What about the following normalized results for two products? Which one is better?



Which one is better?

		A	B
Global warming	Kg CO2-equiv.	6.33E-12	8.55E-12
Ozone layer depletion	Kg CFC-11-equiv.	7.29E-13	7.19E-13
Acidification	Kg SO2-equiv.	3.60E-11	1.00E-11
Human toxicity	kg 1,4-dichlorobenzene eq.	1.28E-15	5.50E-12

- Suppose that relative importance between global warming, ozone layer depletion, acidification and human toxicity are 5:1:2:3. Which product between A and B is better considering relative importance of environmental impact?

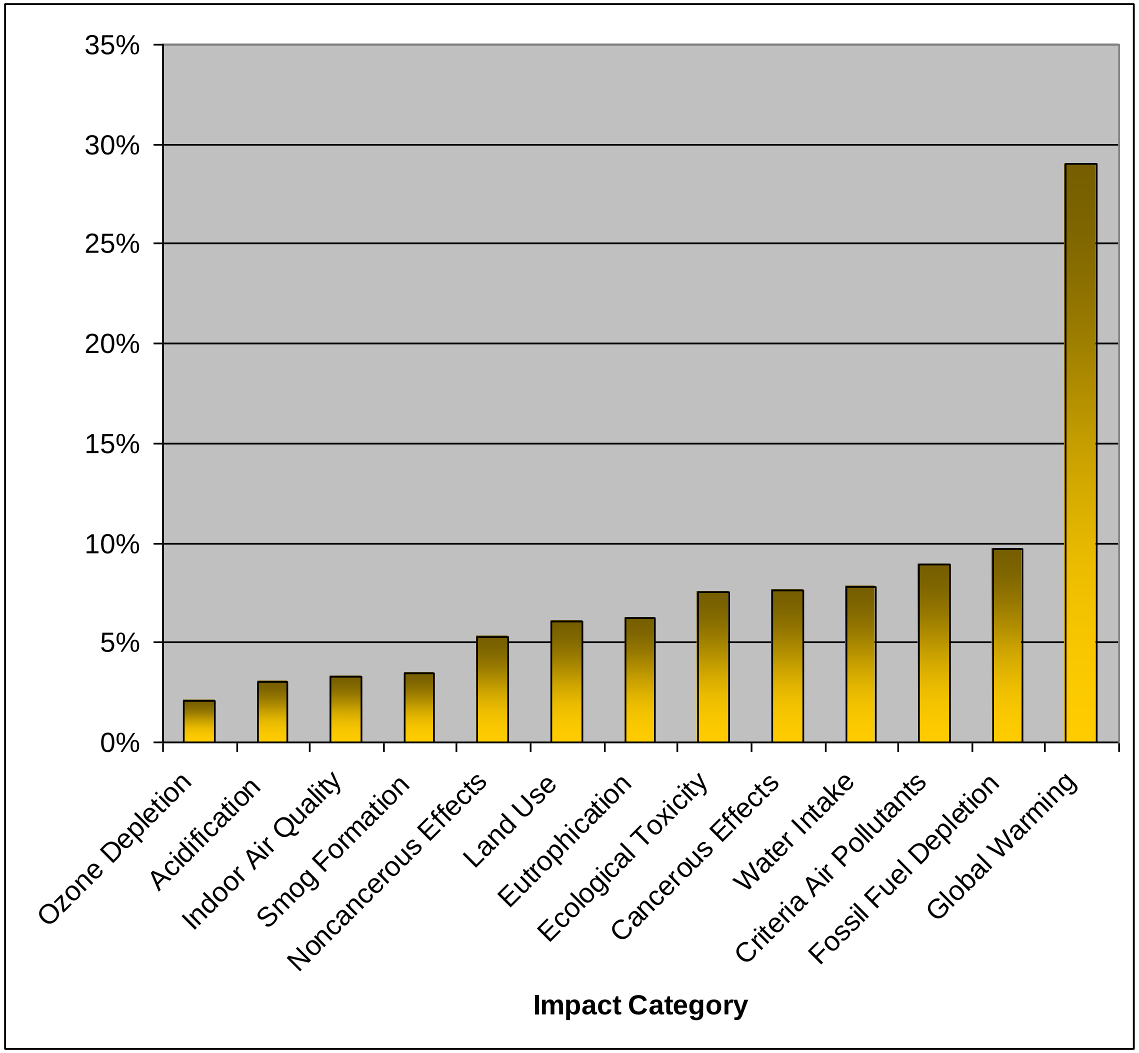
Weighting Calculation

- $$v = \sum_i w_i \frac{c_i}{n_i}$$ where $$c_i = \sum_j f_{ij} m_j$$
- v = weighted results
- w_i = weight of impact category i
- c_i = characterized result of impact category i
- n_i = normalization reference of impact category i

Weighting in Practice

- Distance-to-target method
  - The ratio between the current situation and the policy target serves as a proxy of urgency.
- Panel method
  - Analytical Hierarchy Process (AHP)
  - A systematic method for comparing a list of objectives or alternatives.

Weights by BEES (also used for bioproduct purchasing)



Normalization and Weighting

	A	B	NR	W
Global warming	174	461	6.20E+06	10
Acidification	868	2.4	3.30E+05	2
Photochemical oxidant creation	200	720	9.20E+04	3
Eutrophication	3.5	5.3	5.30E+07	4
Human toxicity	3.40E+11	1.30E+11	8.50E+15	3
Ecotoxicity	2.10E+07	9.60E+06	5.20E+09	4
Land use	170	50	1.30E+05	2

- Calculate normalized results and weighted results. Which product is better?

Recap of the Final AA Report

- A matrix or other summary format;
- A clear visual comparison summarizing the relevant comparison factors;
- The relevant exposure pathways and life cycle segments;
- The Priority Product and each alternative considered;
- The comparative results of evaluating the above information;
- A description of any relevant safeguards provided by other federal and California State regulatory programs that were considered; and
- Selected alternative(s) and recommended next steps.

From AA Guide p163

Summary

- Overview of AA
- Relevance of LCA to AA
- Recap of webinar (Life cycle thinking)
- How can LCA help AA
  - First Stage
  - Second Stage